Airborne Lidar Simulator for the Lidar Surface Topography (LIST) Mission

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ABSTRACT

We report on our continuous progress in developing a multi-beam non-scanning, swath mapping laser altimeter to support the LIdar Surface Topography (LIST) mission. [1] The instrument includes a single laser transmitter, a multi-pixel photon counting detector array, a high bandwidth, sixteen-channel 8-bit digitizer and a high-throughput data system. [2]

INTRODUCTION

In 2009 we started a three-year Instrument Incubator Program (IIP) project, funded by NASA's Earth Science Technology Office (ESTO), for early technology development for the LIST mission. [3] The purpose is to develop and demonstrate technologies for a next-generation, efficient, swath-mapping space laser altimeter. Our approach allows simultaneous measurements of 5-m spatial resolution topography and vegetation vertical structure with decimeter vertical precision in an elevation-imaging swath several km wide from a 400 km altitude Earth orbit. This capability meets the goals of the LIST mission recommended in the Earth Science Decadal Survey by the NRC Committee on Earth Science and Applications from Space. [1] To advance and demonstrate needed technologies for the LIST mission, we are developing a sixteen channel, non-scanning Airborne LIST Simulator (A-LISTS) pathfinder instrument. A-LISTS is a micropulse, photon-sensitive waveform recording system that is based on a new, highly efficient laser measurement approach utilizing emerging laser transmitter and detector technologies. [4]

The A-LISTS instrument uses a single laser to generate sixteen beams for high-resolution mapping. Backscatter from the surface is collected with a telescope and the spots from the swath are imaged onto a photon sensitive detector array. The output from each detector element is histogrammed and analyzed to determine ranges to the surface and derive echo waveforms that characterize the vertical structure of the surface. This signal processing technique allows for through-foliage interrogation in order to observe the ground surface beneath vegetation cover and to characterize vegetation vertical structure.

The returned signal from the ground is captured by a 20 cm diameter ruggedized, athermal telescope. The image of the 4x4 ground pattern is captured by a 4x4 fiber bundle and routed to a 16-element photon-sensitive detector array. The output of this array will be sent to a 16-channel, 1.5 GSamples/s, 8-bit digitizer to record an echo pulse waveform. The detection rate will be controlled to be a few 10's of photons per laser fire per beam by attenuation of the outgoing pulse energy in order to emulate the expected rate of our LIST measurement concept. This approach has the advantage of single photon receiver sensitivity but multiple photon dynamic range and no detector dead-time. In post processing, the waveform output from multiple laser fires along a profile will be aggregated at 5 m spatial scale to yield a composite waveform used for ground detection and canopy structure characterization. The over-sampling along profiles will be used to conduct sensitivity studies to guide refinement of our LIST mission measurement approach.

INSTRUMENT INCUBATOR PROGRAM

Our IIP objectives are to (i) develop key technologies to meet the LIST mission requirements; (ii) provide scalability study for the spaceborne mission; (iii) advancing the technology readiness level (TRL) of critical subsystems; (iv) demonstrate LIST-type measurements over a variety of surface types, including those of vegetation canopy and substructures and (v) validate the micropulse, waveform capturing measurement approach. To meet these objectives, we developed and planned an airborne campaign to demonstrate a 16-channel, non-scanning A-LISTS instrument. We will describe below the instrument and critical subsystems that we developed under this IIP effort.

A. A-LISTS INSTRUMENT

The A-LISTS instrument under development is shown schematically in Figure 1. The laser transmitter output is split with a 95/5 nonpolarizing beam splitter cube. The 5% portion of the light is then further split into two with one part to a start pulse detector that triggers the timing circuit of the altimeter instrument and the second part of the beam will be sent to the receive telescope for illuminating all of the pixels in the detector array. Each of the sixteen pixels will digitize the transmit pulse and use for data processing at a later time. The remaining 95% of the output beam will be divided into 16 beam oriented in a 4x4 grid by a pair of microlens array. [5, 6] These 16 beams will be projected to the ground for altimetry measurement.

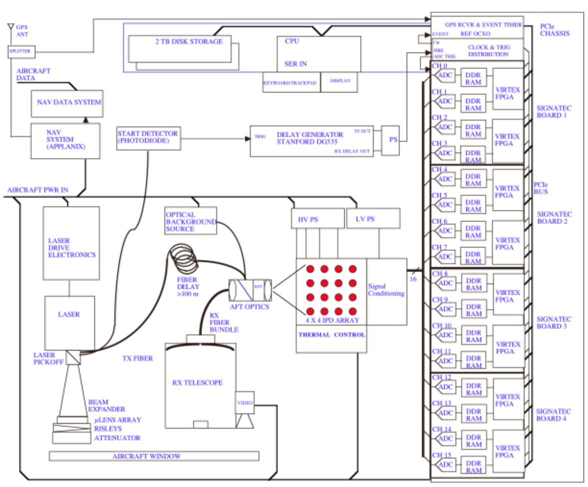


Figure 1. Functional block diagram of the airborne IIP instrument.

The return echo signal will be coupled into a fiber bundle and imaged onto the detector array. The output of the linear mode photon counting array will be digitized using a commercial–off-the-shelf (COTS) 16-channel digitizer with 1.5 GSamples/sec and 8-bit resolution.

The A-LISTS instrument will be installed on a LearJet based out of Glenn Research Center (GRC) in Cleveland. The instrument consists of an optical transceiver and two instrument racks as shown conceptually in Figure 2. The optical transceiver will be installed above the nadir port on the LearJet. Returned signal from the ground will be captured by the telescope and routed to the detector array via a fiber bundle. The two instrument racks located near the optical transceiver will house the power supplies (PS) for both the laser and receiver as well as the data acquisition system (DAS) and a real-time video recorder to capture the fly-over areas along with GPS and time references stamp on the video for reference during post processing. The laser will need to be water cooled with a water chiller and a thermoelectric cooler (TEC) is used inside the laser housing to maintain the temperature of several critical components.

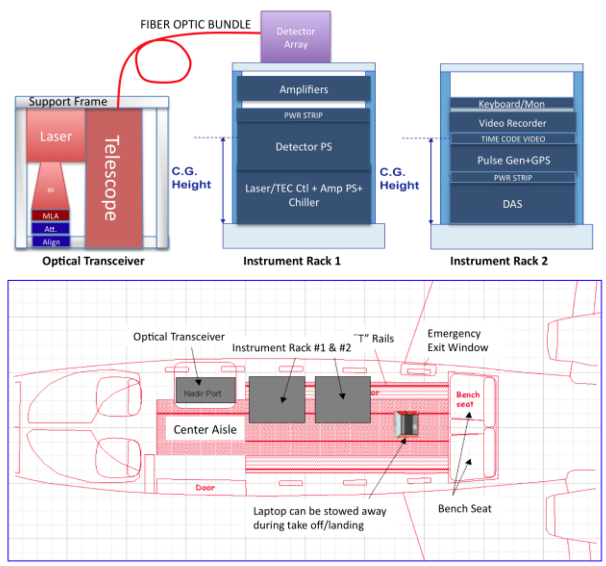
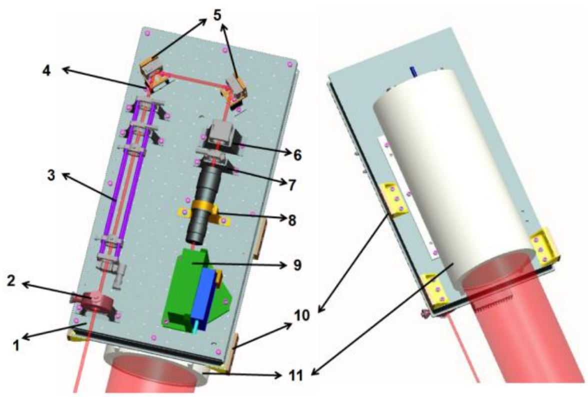


Figure 2. The A-LISTS optical transceiver and to instrument racks and their locations on the LearJet.

For the airborne campaign, the optical transceiver will be housed in an enclosure and mounted to the fuselage over a nadir viewing port. The optical transceiver consists of an optical bench that has the ruggedized telescope on one side and the laser transmitter bench on the other side as shown in Figure 3.

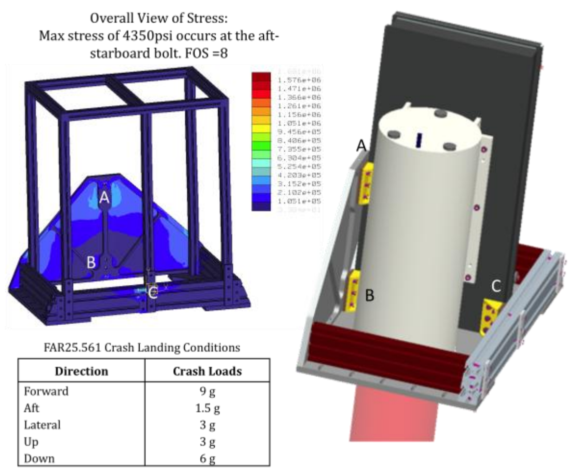
The optical bench is secured to the enclosure with three attachment angle brackets (see Figure 4). Shear and tension calculations were done to ensure the mounting fasteners would survive all crash loading conditions per

FAR 25.5361 and not endanger the integrity of the aircraft.



ITEM	DESCRIPTION	WEIGHT (LBS)
1	Vere Optical Bench	15
2	Beam Steerer	1
3	MLA Assembly	3
4	Various Fasteners	2
5	Turn Mirrors	1.5
6	PBSC	1
7	¼ Waveplate	1.2
8	Beam Expander	1.2
9	Laser Head	5
10	3 attachment angle brackets	1.5
11	Telescope	62
Transceiver Bench Total Weight		95

Figure 3. Bill of Material (BOM) and weights for the A-LISTS transceiver bench. The diagram shows the components of the bench and the mounting brackets securing the bench to the enclosure.



Direction	Crash Loads
Forward	9 g
Aft	1.5 g
Lateral	3 g
Up	3 g
Down	6 g

Figure 4. Shear and tension analysis have been done for the A-LISTS instrument. A representative analysis is shown for the transceiver. The diagram on the right shows the mounting brackets to the mounting frame depicted on the left. A FOS of 8 was calculated based on the most severe forward loading crash conditions of 9g per FAR25.561 as shown in the table above.

For ground testing, the telescope and the laser transmitter are placed side-to-side on an optical bench as shown in Figure 5.

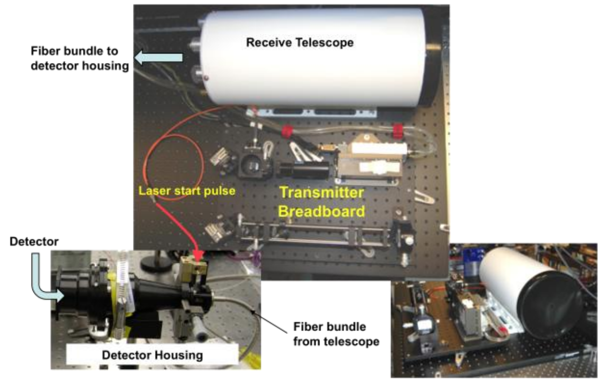


Figure 5. The A-LISTS transceiver for ground testing. The laser transmitter bench is placed next to the receive telescope. Received signal from the telescope is sent to the detector housing assembly via a fiber bundle.

B. *LASER TRANSMITTER*

The A-LISTS instrument uses a passively q-switched Yb:YAG master oscillator (MO) that delivers a 2 – 10 kHz repetition rate, 100 µJ pulse energy and <1 ns pulse width output. [7] The laser is single frequency with about a 2 pm spectral width (<16 pm) jitter over a three-hour duration. The center wavelength is 1030.14 nm (see Figure 6).

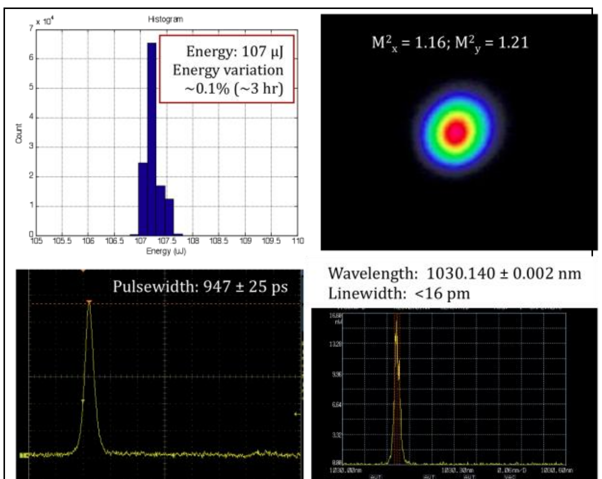


Figure 6. The master oscillator is capable of delivering ~100 µJ at < 1nS pulse width, M^2 ~ 1.2 and centered at 1030.14 nm.

We are also working with Raytheon Space and Airborne Systems on a master oscillator power amplifier (MOPA) using the MO as the seed and a planar waveguide amplifier (PWA) [8] to provide a single pass gain of about 16. The overall output energy of the MOPA laser is ~1.6 mJ. The overall dimension of the MOPA laser housing is 18” x 12” x 7” as shown in Figure 7.

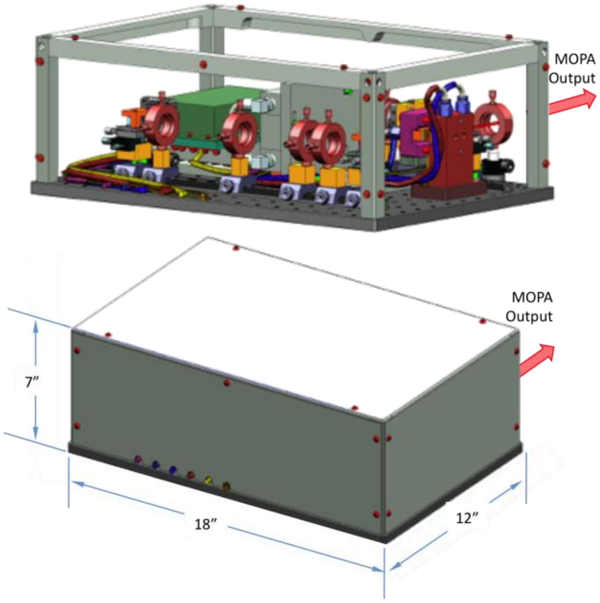


Figure 7. The MOPA laser is a Yb:YAG MO with a PWA to boost the energy from 0.1 mJ to 1.6 mJ with 10 kHz and < 1 ns pulse width.

C. DETECTOR AND DATA SYSTEM

Another critical technology for LIST is high–sensitivity low-noise detectors that provide single-photon sensitivity. The backscatter laser signals by surface and biomass (e.g. grass, trees, etc.) at the satellite altitude are very weak. Detectors with high quantum efficiency (QE) and internal gain are needed to overcome detector amplifier noise and achieve the required signal-to-noise ratios. Our baseline detector is an Intevac high bandwidth, 4x4 InGaAsP multi-element anode intensified photodiode (IPD) array that has >20% quantum efficiency (QE) at 1 µm wavelength, dark count of <0.5 MCounts/second/pixel and gain of >10,000 (see Figure 8). [9]

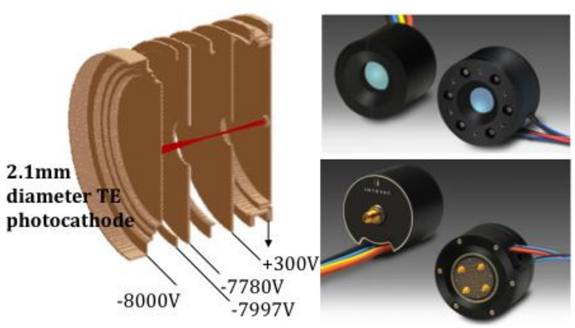


Figure 8. 4X4 InGaAsP IPDs developed by Intevac will be used in this IIP.

The alternative detector for the A-LISTS instrument is the impact-ionization-engineered InAlAs Avalanche Photodiodes (APDs) from Spectrolab. [10]

We have designed a detector housing assembly that can accommodate either detector for the airborne campaign. The detector housing consists of an interface with an input fiber bundle, a narrow bandpass filter, an adjustable iris and focusing lenses to either the Intevac IPD or an output fiber bundle to the Spectrolab detector assembly. The filter, which will be used to block out solar background, is centered at the MO output wavelength of 1030.14 nm, a full width at half maximum of 0.85 nm and >85% transmission. The adjustable iris has a 100% closure will be used for dark count calibration and intensity adjustment for the detectors.

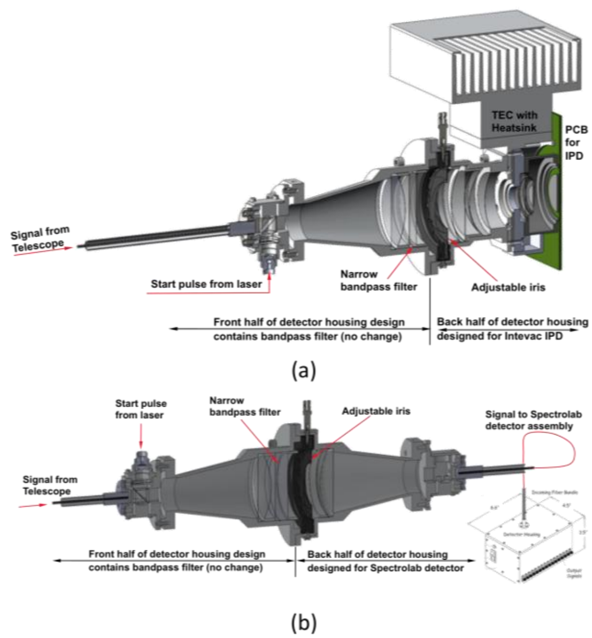
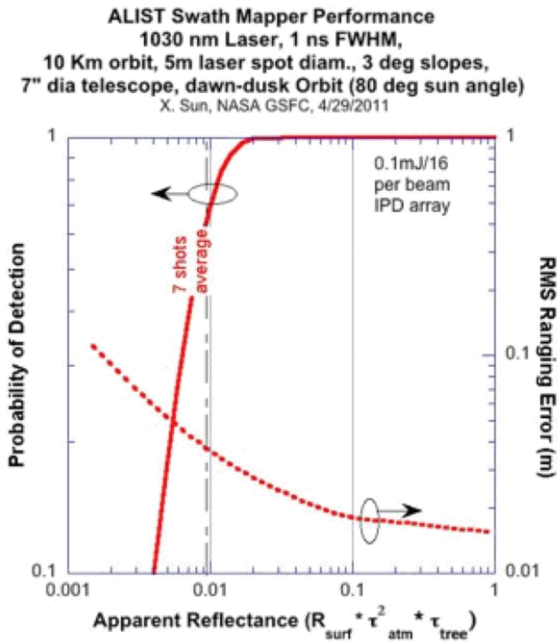


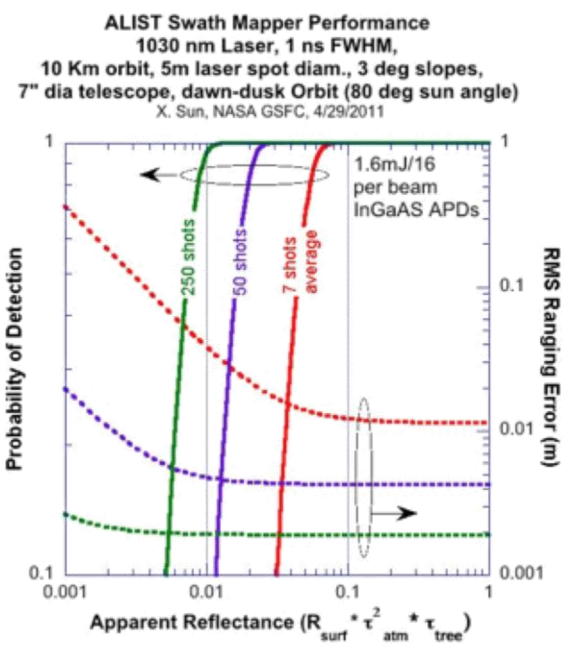
Figure 9. Detector housing for (a) Intevac IPD and (b) Spectrolab APDs. The housing is designed to accommodate both detectors with minimal hardware removal.

The returned signal as received by the telescope will be routed to the detector housing by a 4x4 fiber bundle. The signal will then be collimated then go through a filter and adjustable iris. This is where the mechanical interface is different depending on which detector to use. In Figure 9a, the signal continues on and will be re-focused directly on the Intevac IPD. The TEC with heatsink shown in the figure is for cooling of the Intevac IPD. The Intevac IPD is placed on the PCB (printed circuit board) and mounted directly to the detector housing. The PCB has 16 electrical connections, from each of the pixels, which will be connected to the 16-channel digitizer for data processing and collection.

In case of the Spectrolab APDs assembly, as shown in Figure 9b, the signal after the adjustable iris will then be focused on a fiber bundle. This fiber bundle will be the interface to the Spectrolab sixteen APDs. The rf signal output from the APDs will then be connected to the digitizer as described earlier.



(a)



(b)

Figure 10. Link analysis for the A-LISTS instrument using the Intevac IPD and Spectrolab APD from 10 km altitude with a 7" receive telescope.

Link analysis of the A-LISTS instrument using both the Intevac and Spectrolab detectors have been performed. In the case of the Intevac detector (Figure 9a) the analysis showed a probability of detection of >0.7 can be obtained by aggregating over 7 shots (similar to the LIST spaceborne scenario, from 400 km orbit with spacecraft speed of ~7km/s, we can accumulate 7 shots over a 5-m foot print) with an apparent reflectance of ~0.01 and laser energy of ~100 μJ spread evenly over 16 channels. In this case, the MO along will be able to provide the energy for the link from 10 km.

For the case of the Spectrolab APD detectors (Figure 10b), for the same apparent reflectance of 0.01, we need to aggregate over ~250 shots and with higher energy per pulse to achieve a ~0.8 probability of detection. The energy requirement is ~1.6 mJ distributed evenly over 16 channels. This will require the use of the MOPA laser.

We planned on performing flights with both configuration to advance the TRL of the MOPA and detectors.

The output of this array will be sent to a commercial off-the-shelf (COTS) 16-channel, 1.5 GSamples/s digitizer. The digitizer output will be fed into a flight computer. The flight computer manages the data flow from both the digitizer and navigation sensor with appropriate time stamps and stores them at a sustainable rate of about 500 MB/s. Flight software for both airborne and ground systems are also being developed. The airborne software will provide digitizer initialization, acquire data from each of the sixteen channels, perform aliveness tests, display limited real-time in-flight data, and write the data to removable hard drives. The airborne software will also collect and store navigation and housekeeping data. Upon completion of a flight test, the hard drives will be moved to an identical ground station computer system. The ground computer system will back up the data and generate science data products.

D. OPTICAL SYSTEM

The airborne altimetry system will demonstrate a 16-beam version of the LIST instrument. The sixteen beams orient in a 4x4 grid pattern with uniform spacing between spots. The overall dimension of the grid is 75 m x 75 m (7.5 mrad x 7.5 mrad) with 20 m (2mrad) between spots. The grid will have a 14.5°±1° clocking with respect to the aircraft velocity vector to yield an effective 5m spot cross-track spacing as shown in Figure 11. A pair of microlens array will be used to divide a single beam into 16 beams (Figure 12). [5]

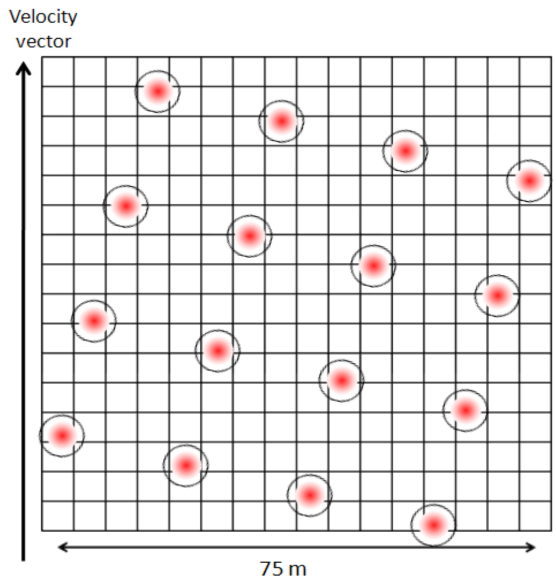


Figure 11. This figure illustrates the baseline footprint configuration of the IIP airborne lidar from 10 km altitude. The solid circles are the 5 m laser footprints with the open circles showing the detector field of view of ~7 m.

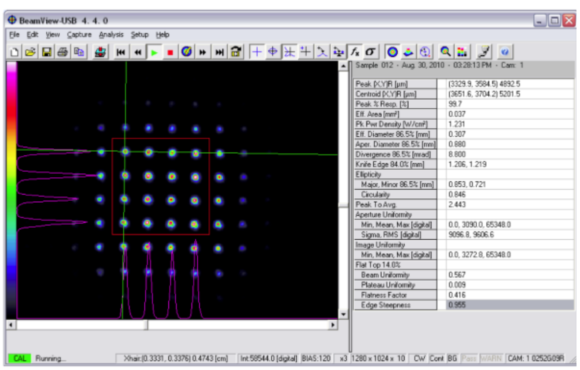


Figure 12. The figure shows the actual beam pattern generated with a pair of microlens array. A single beam input is split evenly into a 5x5 grid with equal intensity.

E. AIRBORNE DEMONSTRATION

We are in the process of doing end-to-end ground demonstration and then proceed to airborne campaign in late summer 2011. We will leverage our recent experience on a micropulse lidar airplane demonstration. [11] Previously we demonstrated a lidar with a 1 µJ per beam, a 10 KHz laser, and a single-photon-threshold detector (Geiger-mode APD) based receiver. Our new lidar using micropulse photon-counting approach will demonstrate a laser with 100 µJ per beam, a 10 kHz pulse rate, and a receiver using single-photon-sensitive analog-mode detector and waveform-digitizer.

Our plan is to operate the instrument at a 10 km altitude. A number of flight tests over different regions are being considered. Candidate regions for the tests will be selected to demonstrate measurement concept that satisfy the LIST science objectives of mapping in cryosphere, water cycle, vegetation structure and solid Earth application areas.

CONCLUSIONS

We continued to develop the measurement approach and lidar technologies for the LIST lidar mission requirements by demonstrating the A-LISTS instrument. The objectives are to mitigate the major risks and developing measurement techniques for the LIST mission. Our plans are to incorporate the work on the measurement approach and lidar technologies developed during the first two years into an airborne lidar simulator, and to demonstrate measurements in summer 2011.

ACKNOWLEDGMENT

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